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COMPARATIVE ANALYSIS OF POLYPHENOL CONTENT, ANTIOXIDANT ACTIVITY AND ANTIMICROBIAL PROPERTIES IN ENDEMIC AND WIDESPREAD ALLIUM SPECIES OF TAJIKISTAN

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Abstract

In Tajikistan, the Allium genus is notably prolific, with over 80 species documented, and new species continually being identified in the mountainous regions. The Gorno-Badakhshan Autonomous Region (GBAO) of Tajikistan, within the Pamir Mountains, is significant for its 31 distinct Allium species, including endemics like A. afghanicum Wendelbo and A. schugnanicum Vved. The distribution of these species is often geographically restricted, and their biological activities, especially their antimicrobial properties, remain largely unexplored, presenting significant opportunities for future phytochemical and pharmacological research. This scholarly inquiry is aimed at contributing substantially to the academic discourse on the therapeutic capacities of Allium species, focusing particularly on their polyphenolic profiles and resultant bioactive functionalities. Our investigation revealed distinct correlations between antioxidant activity and antibacterial efficacy across different parts of selected Allium species. Notably, antioxidant activities in A. altaicum leaves and A. elatum flowers exhibited positive correlations with antibacterial effects against Staphylococcus aureus. Additionally, the bulbs of A. suworowii demonstrated a moderate positive correlation in this regard. Conversely, negative correlations were identified for P. aeruginosa in the bulbs of A. oschaninii, A. schoenoprasum, and A. sativum. Particularly striking was the strong negative correlation between antioxidant activity and the anti - E. coli effect observed in A. hymenorhizum flowers. Furthermore, the leaves of A. oschaninii and A. schugnanicum exhibited contrasting correlations with antibacterial effects, underscoring the complex interplay between antioxidant activity and antibacterial efficacy within these species. These findings suggest that the relationship between antioxidant activity and antibacterial effects is not uniform across all Allium species or bacterial strains. The observed variability implies that factors beyond antioxidant activity per se may influence the antibacterial potential of these plant extracts.

Key words: Allium species, polyphenol content, antioxidant activity, antimicrobial and anfungal properties, test microorganisms

I. INTRODUCTION

The *Allium* genus, comprising petaloid perennial herbs, is distinctly characterized by its linear leaves with parallel venation and the presence of tunicate bulbs, occasionally situated on rhizomes. Predominantly thriving in the warm-temperate, temperate, and boreal zones of the Northern Hemisphere, *Allium* species are notable for their unique alliaceous odor and flavor, a characteristic attributed to sulfur-containing compounds [1]. Taxonomically situated under the *Amaryllidaceae* family as per the APG IV system [2]. *Allium* comprises an estimated 1000 species [3, 4, 5].

Central Asia, especially the Central Asiatic Region, is a biodiversity hotspot for *Allium*, harboring over two hundred species. This region is considered the center of origin for key cultivars such as onion (*A. cepa* L.) and garlic (*A. sativum* L.) [6, 7]. Historically, the Silk Road facilitated plant exchanges between East and West, enhancing this region's role in plant conservation and development under the Belt and Road Initiative [8].

In Tajikistan, the *Allium* genus is notably prolific, with over 80 species documented, and new species continually being identified in the mountainous regions. The Mountainous-Badakhshan Autonomous Region (MBAR) of Tajikistan, within the Pamir Mountains, is significant for its 31 distinct *Allium* species, including endemics like *Allium afghanicum* Wendelbo and *Allium schugnanicum* Vved. The distribution of these species is often geographically restricted, and their biological activities, especially their antimicrobial properties, remain largely unexplored, presenting significant opportunities for future phytochemical and pharmacological research [9, 10].

Allium plants are historically significant for their extensive applications in gastronomy, traditional medicine, and horticulture. A recent study in the satoyama ecosystems of the Noto Peninsula, Japan, highlights the utilization of at least four wild *Allium* species for diverse ethno botanical purposes [11]. Archaeobotanical evidence suggests the consumption of *Allium* species as early as 7000 BC in regions such as Central Asia and the Middle East. The antibacterial properties of garlic were first reported by Louis Pasteur [12]. Garlic represents one of the earliest instances of an *Allium* species being developed into a global agricultural crop, valued for its culinary and vegetative properties [13].

Wild *Allium* species represent a vital genetic reservoir for enhancing cultivated *Allium* crops, offering a diverse array of genetic resources for agronomic improvement [14]. Plant secondary metabolites, including phenolics, terpenes, and nitrogen-containing compounds, are increasingly recognized for their roles in pharmaceutical, nutritional, and agricultural applications. These compounds are integral to plant responses to environmental stresses. *Allium* plants exhibit a multitude of nutritional, biological, and health-promoting properties, including antimicrobial, antioxidant, antitumor, immunoregulatory, antidiabetic, and anti-inflammatory effects, indicating their potential utility in the treatment of various diseases [15[.

Plant secondary metabolites, the generic term for more than 12,000 alkaloids, 40,000 terpenoids, and 8000 phenylpropanoids, are exclusively produced by plants [16]. *Allium* species, both cultivated and wild, are known to synthesize an abundance of secondary metabolites, including saponins, organosulfur compounds, and flavonoids, which exhibit a range of bioactivities from

antioxidant to anti-inflammatory properties [17, 18]. This highlights the growing interest in exploiting *Allium* species for novel functional products in pharmaceutical and food industries, underscoring the potential of *Allium*-derived saponins as sources of innovative bioactive molecules [19]. In addition, polyphenols, a diverse group of secondary metabolites present in plants, are synthesized via the shikimate and acetate-malonate pathways. These compounds, with over 10,000 distinct types, are crucial for various physiological and biochemical plant processes and have several medical applications [20].

Oxidative stress is characterized by an imbalance between the production of free radicals and reactive metabolites, known collectively as oxidants or reactive oxygen species (ROS). These entities include both radical and non-radical forms. Such an imbalance can result in damage to critical biomolecules and cells, potentially leading to systemic effects on the organism. A considerable body of research has demonstrated that bioactive compounds found in *Allium* species interact with ROS, highlighting their potential therapeutic value in pharmacology for treating diseases of various origins. Specifically, polyphenols are thought to serve as antioxidants, employing mechanisms such as scavenging free radicals and interacting with other physiological antioxidants [21, 22]. The ABTS assay for antioxidative activity is among the most widely used comprehensive methods to assess antioxidant activity [23, 24, 25].

Driven by concerns about the safety of synthetic chemicals and the rise of drug-resistant pathogens, natural extracts with antibacterial activity and favorable biocompatibility are attracting significant interest. Polyphenols, notably, have bacteriostatic or bactericidal effects against both Gram-positive and Gram-negative bacteria, making them a rich source of potential drugs for inhibiting bacterial growth [26].

Recent scholarly research has elucidated that the quantification of total polyphenolic content and associated antioxidant properties in plants, specifically within the *Allium* genus, are significantly modulated by a complex interplay of biological variables. These include genetic determinants, the developmental stage of specific organs, and the overall physiological maturation, all of which are intricately influenced by edaphic and environmental factors [27, 28, 29, 30].

Additionally, external factors such as biotic stress, plant age, photic conditions, and prevailing climatic conditions critically contribute to the biosynthesis and accumulation of phenolic compounds, with direct implications for the plant's functional role and phonological development [31, 32]. This knowledge is vital for comprehending the correlation between polyphenolic profiles and antioxidant activity in *Allium* species endemic to the mountainous regions of Tajikistan.

Allium species native to Tajikistan's mountainous regions are a crucial source of unique genetic material. The high-altitude environment of the Himalayan cold desert, abundant in natural resources, presents extreme climatic challenges for plants, including intense mutagenic UV radiation, drought, desiccation, and strong winds. To adapt, these plants have evolved to produce distinct metabolites crucial for survival. Notably, they synthesize a range of nonenzymatic antioxidants, effective against oxidative damage from ROS. Their antioxidant capabilities are largely due to secondary metabolites like phenolic acids, diterpenes, flavonoids, and volatile oils, with some plant pigments such as anthocyanins also contributing [33].

The present study is meticulously structured to quantitatively analyze the polyphenolic content and the scope of antioxidant activities in fifteen *Allium* species, with a specialized emphasis on two endemic *Alliums* native to the elevated terrains of the Republic of Tajikistan. Furthermore, this investigation endeavors to decipher the intricate correlation between these phytochemical properties and the intrinsic antibacterial and antifungal attributes of the plants. This scholarly inquiry is aimed at contributing substantially to the academic discourse on the therapeutic capacities of *Allium* species, focusing particularly on their polyphenolic profiles and resultant bioactive functionalities.

II. MATERIALS AND METHODS

II.1. Plant Collection. Fifteen wild species of the genus *Allium* were meticulously collected from various locations within the picturesque Shughnon Range in the Mountainous - Badakhshan Autonomous Region, Tajikistan. The specimens included inflorescences (flowers), leaves, and bulbs. The species collected were: *A. altaicum* Pall., *A. carolinianum* DC., *A. elatum* Regel, *A. hymenorhizum* Ledeb., *A. longicuspis* Regel, *A. nutans* L., *A. obliquum* L., *A. oschaninii* O. Fedtsch., *A. pamiricum* Wendelbo, *A. ramosum* L., *A. sativum* L., *A. schoenoprasum* L., *A. schugnanicum* Vved., *A. senescens* L., and *A. suworowii* Regel. The GPS coordinates, elevation, and topographical characteristics of the collection sites were meticulously documented.

II.2. Chemicals. The analytical reagents used in this study were sourced as follows: Folin-Ciocalteu's phenol reagent and ABTS [2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)] from Sigma-Aldrich, St. Louis, MO; Sodium Carbonate from Fisher Scientific Co., Fair Lawn, NJ; Potassium persulfate from JTBaker Chemical Co., Phillipsburg, NJ; and Gallic Acid Monohydrate from Acros Organics, Morris Plains, NJ.

II.3. Plant Extract Preparation. Ethanol extracts from various parts of *Allium* species were prepared with slight modifications to the previously described RAMES method [34]. Initially, collected plant materials—including flowers, leaves, and bulbs—were finely chopped into smaller pieces. The total weight of the combined plant materials was standardized to two grams, using a portable balance (CS Series, Ohaus, Parsippany, NJ). These fragments were then transferred to labeled 20 ml scintillation vials. Using a sterile syringe, exactly four milliliters of 95% ethanol were measured and added to each vial. The plant tissue underwent a simultaneous grinding and extraction process, utilizing a cordless, variable-speed Dremel rotary tool, Model 8220 (12V), for a period of 5 minutes. This process facilitated the thorough mixing of the plant components with ethanol. The resulting slurry was then syringe-filtered through glass fiber filter paper, producing the final ethanol extract for further analysis.

II.4. Disc preparation. The antimicrobial and antifungal activities of the plant extracts were evaluated using discs impregnated with the extracts, prepared according to the method detailed in references [35]. Initially, the extracts in the vials were allowed to settle for at least five minutes before filtration. Next, 90 µL of the filtered plant extract were uniformly applied to 10 mm diameter Whatman glass microfiber filter discs, Grade GF/D (Whatman # 1823±010, sourced from Millipore Sigma). Care was taken to ensure the extract was evenly distributed across the disc to prevent areas of over-concentration. Once the extracts were applied, the discs were air-dried at room temperature.

The dried discs were then stored in pre-labeled plastic bags for subsequent antimicrobial and antifungal testing.

II.5. Microorganisms. The obtained extracts were subjected to antimicrobial efficacy testing against a selection of reference microbial strains. The bacterial panel for this assessment comprised *Staphylococcus aureus* Rosenbach (ATCC 4929), *Escherichia coli* (Migula) Castellani and Chalmers (ATCC 4928), *Pseudomonas aeruginosa* (Schroeter) Migula (ATCC 4930), and *Klebsiella pneumoniae* (Schroeter) Trevisan (ATCC 4927). In addition to the bacterial strains, antifungal activity was evaluated against *Candida albicans* Berkhout, a commonly encountered fungal species.

II.6. Culture media. Specific culture media were utilized for the cultivation of reference bacterial strains. Mueller Hinton Agar was selected for *S. aureus*, King's A medium for *P. aeruginosa*, a specialized Klebsiella 5-ASK 20 medium for *K.pneumoniae*, and both Endo's and Levin's media were used for *E. coli*.

II.7. Inoculum preparation. Bacterial strains were initially seeded on the surface of their respective nutrient media in Petri dishes: *S. aureus* on Mueller Hinton Agar, *E. coli* on Endo medium, *P. aeruginosa* on King A medium, and *K. pneumoniae* on Klebsiella-5-ASA 20. To ensure culture purity, an isolated colony from each strain was subsequently cultured on corresponding slant agar media. Suspensions (inocula) were then prepared from daily cultures at a McFarland turbidity standard of 10 IU, adjusting the concentration of microorganisms to 2×10^6 $CFUml^{-1}$.

II.8. Antimicrobial assays. The antibacterial activity of the plant extracts was determined using a modified Kirby-Bauer disk diffusion method (Hudzicki 2009). This involved inoculating plates with nutrient medium with a previously diluted suspension of the microorganisms. Extract-impregnated discs were then placed on the agar surface, spaced 1.5-2 cm apart. All plates were incubated at 37°C for 18-24 hours, after which the inhibition zones around the discs were measured to assess bacterial growth inhibition.

II.9. Antifungal assay. The antifungal efficacy was assessed using a protocol similar to the antimicrobial assays. A prepared *C. albicans* inoculum was spread onto sterile Sabouraud Dextrose Agar (SDA) plates. The evaluation process mirrored that used for the bacterial strains, with zones of inhibition around the extract-impregnated discs indicating antifungal activity.

II.10. Total polyphenolic content (Folin-Ciocalteu) assay. The estimation of the Total Phenolic Content (TPC) in the plant extracts was performed using a Folin-Ciocalteu reagent-based method, adhering to a well-established protocol [36] with minor modifications for enhanced reliability. Briefly, to each Eppendorf tube, 200 µL of the plant extract was added, followed by an equal volume of 1N Folin-Ciocalteu reagent. The mixture was incubated at room temperature for 10 minutes before adding 300 µL of a 20% sodium carbonate (Na_2CO_3) solution. After vigorous shaking, the tubes were incubated at 40°C for 20 minutes and then quickly cooled to room temperature. Absorbance was measured at 760 nm using a portable USB-650-VIS-NIR Red Tide Spectrometer, interfaced with SpectraSuite software. The TPC was quantified using a gallic acid standard curve, with dilutions made as necessary to ensure sample concentrations fell within the curve's linear range. Results were reported as micrograms of Gallic Acid Equivalents (GAE) per gram of fresh weight (µg GAE g^{-1}).

II.11. ABTS antioxidant activity assay. The antioxidant activity of plant extracts was assessed using the ABTS assay, a widely recognized method for evaluating plant-based samples, modified slightly from the procedure described by Walker and Everette [37, 38]. Briefly, the ABTS assay determines the radical scavenging ability of plant extracts through their interaction with the ABTS radical cation, generated by the action of potassium persulfate ($K_2S_2O_8$). This reaction transforms the ABTS solution from colorless to a dark green hue. The presence of antioxidants in the plant extracts reverses this color change, indicating scavenging activity by converting the dark green ABTS radical cation back to its neutral, colorless state.ATrolox solution, a water-soluble vitamin E analog, served as the reference standard for the assay. Absorbance measurements were performed at 734 nm using a portable USB-650-VIS-NIR Red Tide Spectrometer, coupled with SpectraSuite software. To ensure accuracy, extracts were diluted as needed to fit within the linear range of the Trolox standard curve. Results were expressed in micrograms of Trolox Equivalents (TE) per gram of fresh weight (μg TE g^{-1}).

II.12. Statistical analysis. Statistical analyses were conducted using the Statistica 10.0 software package (Statsoft, USA). The Shapiro-Wilk test was employed to verify the normal distribution of the sample data. Results were presented as arithmetic means ± standard error, with sample sizes of n=10. For pairwise comparisons of relative values, the χ^2 test with Yates correction and the Friedman test were utilized. The Kruskal-Wallis H-test facilitated the comparison of multiple independent quantitative groups.Nonparametric analyses included the Mann-Whitney U test for comparing independent samples and the Wilcoxon T-test for dependent samples. The Pearson correlation coefficient was calculated to determine the linear correlation between two datasets. The degree of correlation was classified as perfect (r=1.0), very high (0.9<r<1.0), high (0.7<r≤0.9), moderate (0.5<r≤0.7), low (0.3<r≤0.5), weak (0.0<r≤0.3), or absent (r=0.0), with negative correlations indicated by a "-" sign. Additionally, the ANOVA method and the Student's t-test with Bonferroni correction were applied to assess the experimental results. Statistical significance was assigned to differences with a p-value < 0.05.

III. THE RESULT AND CONDUCTED RESEARCH

III.1. Polyphenolic content variability in Allium genus species: comparative analysis of aboveground and underground parts. This study presents a comprehensive evaluation of the polyphenolic content in both aboveground and underground parts of fifteen *Allium* species using ethanol extracts. The analysis reveals broad variability in the TPC across different species and plant parts, with gallic acid as a standard (Table 1).The overall variability in the TPC is lower in flowers compared to leaves and bulbs. The lowest TPC was reported for the flowers of *A. ramosum* (10.50 ± 0.28 μg GAE g^{-1}) and the highest in the flowers of *A. obliquum* (16.50 ± 0.09 μg GAE g^{-1}).

The findings indicate that the TPC in the leaves of investigated *Allium* species ranged from 10.84 ± 0.06 μg GAE g^{-1} to 21.06 ± 0.07 μg GAE g^{-1}. Notably, significant differences in TPC levels were observed among several species, including *A. suworowii*(21.06 ± 0.07 μg GAE g^{-1}), *A. oshaninii* (19.02 ± 0.08 μg GAE g^{-1}), *A. sativum*, and *A. obliquum* (15.02 ± 0.07 μg GAE g^{-1}). A range of 10.84 ± 0.06 μg GAE g^{-1} to 14.22 ± 0.05 μg GAE g^{-1} was recorded in other species (p = 0.000). Endemic

species such as *A. pamiricum* and *A. schugnanicum* exhibited a consistently low and uniform TPC ($p > 0.05$).

In bulb extracts, a high TPC, exceeding 20 µg GAE g^{-1}, was found in *A. oshaninii*, *A. senescens*, *A. obliquum*, *A. sativum*, *A. elatum*, *A. shugnanicum*, *A. carolinianum*, and *A. nutans*, with the highest level of 23.28 ± 0.11 µg GAE g^{-1} reported for *A. oshaninii*. The lowest TPC was observed in the bulbs of *A. longicuspis* (13.04 ± 0.06 µg GAE g^{-1}).

Overall, the bulb has the highest content of TPC, followed by the leave, and then the flowers. This trend, however, is not universal across all species. Notably, the TPC in flowers and leaves can be very close, and in some cases, such as with *A. carolinianum*, *A. elatum*, *A. longicuspis*, *A. obliquum*, and *A. sativum*, the reported TPC in flowers was somewhat higher than in leaves.

III.2. Antioxidant activity variability in Allium genus species: comparative analysis of above ground and underground parts.

Table 1 illustrates the antioxidant activity across various plant parts. The analysis revealed that the antioxidant activity across different plant parts of the *Allium* species generally fluctuated within a relatively narrow range. The lowest recorded activity was 9.10±0.17 µg TE g^{-1} in the leaves of *A. schugnanicum*, while the highest was 13.30±0.05 µg TE g^{-1} in the flowers of *A. elatum*. Notably, two species, *A. carolinianum* and *A. elatum*, exhibited significantly higher antioxidant activity in their

Table 1. Total content of polyphenol and antioxidant activity of *Allium* species. Arithmetic mean ± standard error (n=10), p -Friedman test, p_0 - Kruskal-Wallis H-test.

Species	Total Polyphenol (µg GAE g^{-1})			p	Antioxidant Activity (µg TE g^{-1})			p
	Flowers	Leaves	Bulb		Flowers	Leaves	Bulb	
A. altaicum	12.24±0.16	12.36±0.11	19.40±0.08	=0.001 χ^2 =15.00	11.04±0.06	10.66±0.09	11.34±0.06	=0.014 χ^2 =8.60
A. carolinianum	14.18±0.13	12.46±0.12	21.08±0.10	=0.000 χ^2 =20.00	12.02±0.07	11.24±0.04	10.84±0.15	=0.008 χ^2 =9.80
A. elatum	13.00±0.02	12.20±0.03	21.60±0.07	=0.000 χ^2 =20.00	13.30±0.05	10.76±0.04	10.54±0.03	=0.000 χ^2 =19.54
A. hymenorhizum	11.42±0.18	11.68±0.08	17.66±0.39	=0.007 χ^2 =9.90	10.36±0.03	10.44±0.03	11.2±0.05	=0.001 χ^2 =15.20
A. longicuspis	11.66±0.04	10.84±0.06	13.04±0.06	=0.000 χ^2 =20.00	10.78±0.05	10.24±0.07	10.94±0.07	=0.005 χ^2 =10.40

A. nutans	11.60±0.05	14.22±0.05	20.32±0.06	=0.000 χ^2 =20.00	10.70±0.04	10.64±0.05	10.88±0.06	>0.05 χ^2 =0.80
A. obliquum	16.50±0.09	15.02±0.07	21.32±0.17	=0.000 χ^2 =19.54	9.82±0.12	10.36±0.02	10.42±0.05	>0.05 χ^2 =1.80
A. oshaninii	12.18±0.06	19.02±0.08	23.28±0.11	=0.000 χ^2 =20.00	10.7±0.05	10.28±0.16	10.66±0.04	>0.05 χ^2 =3.80
A. pamiricum	10.88±0.12	13.04±0.03	17.62±0.05	=0.000 χ^2 =20.00	10.9±0.04	10.74±0.06	10.86±0.03	>0.05 χ^2 =0.60
A. ramosum	10.50±0.28	13.08±0.15	16.86±0.12	=0.000 χ^2 =18.20	10.46±0.06	10.54±0.04	11.00±0.03	=0.002 χ^2 =12.60
A. sativum	16.50±0.09	15.02±0.07	21.32±0.17	=0.000 χ^2 =19.50	9.7±0.05	9.64±0.08	10.5±0.04	=0.000 χ^2 =16.00
A. schugnanicum	11.84±0.05	13.58±0.04	21.12±0.11	=0.000 χ^2 =20.00	10.04±0.09	9.10±0.17	10.10±0.07	=0.035 χ^2 =6.69
A. senescens	13.04±0.07	13.14±0.07	22.80±0.09	=0.001 χ^2 =15.20	10.42±0.02	10.02±0.19	10.64±0.16	=0.014 χ^2 =8.60
A. shoenoprasum	10.70±0.05	13.12±0.06	15.78±0.16	=0.000 χ^2 =20.00	10.58±0.04	10.44±0.03	11.10±0.06	=0.002 χ^2 =12.60
A. suworowii	11.82±0.23	21.06±0.07	21.36±0.11	=0.000 χ^2 =15.80	10.78±0.04	10.04±0.17	10.9±0.11	=0.005 χ^2 =10.40
p_0	=0.000 df =14; H =122.37	=0.000 df =14; H =133.82	=0.000 df =14; H =132.56		=0.000 df =14; H =107.13	=0.000 df =14; H =77.83	=0.000 df =14; H =67.08	

flowers compared to their leaves and bulbs. Additionally, a modest yet statistically significant increase in antioxidant activity in the bulbs was observed in several species, including *A. altaicum*, *A. hymenorhizum*, *A. longicuspis*, *A. ramosum*, *A. sativum*, *A. schugnanicum*, *A. senescens*, *A. shoenoprasum*, and *A. suworowii*. However, the remaining species did not demonstrate any significant differences in antioxidant activity among the different plant parts. Overall, the data did not reveal a consistent pattern in the distribution of antioxidant activity across the various plant parts of the *Allium* species under study.

III.3. Correlation between the content of total polyphenol and antioxidant activity of ethanol extracts with their antibacterial and antifungal activities.

This study investigated the correlation between the content of TPC and the antioxidant activity in ethanol extracts from various plant parts and their antibacterial and antifungal activities, as delineated in the Statistical Analysis section.

III.3.1. Antibacterial effects of plant extracts against Staphylococcus aureus.In this study, we observed a range of relationships between the TPC and antioxidant activity, and their anti-staphylococcal effects in the evaluated plantextracts. Theserelationshipsvaried, exhibitinghigh positive correlations (upto r=0.80) and moderate negative correlations (down to r=-0.64). Notably, the majority of the studied extracts showed no statistically significant correlation.

As outline din Table 2, a statistically significant and pronounced positive correlation was noted between the antioxidant activity and the anti-staphylococcal effect in the leaf extracts of *A. altaicum* (r = 0.80, P = 0.006). Similarly, the flower extracts of *A. elatum* also demonstrated a significant high positive correlation (r = 0.77, p = 0.009) interms of antioxidant activity and anti-staphylococcal effect.

Table 2. Correlation between the total polyphenol content and antioxidant activity with the anti-staphylococcal effect of plant extracts

Species	Plantpart	Total Polyphenol		Antioxidant Activity	
		r	P	r	P
A. altaicum	Flowers	0.06	>0.050	0.07	>0.0500
	Leaves	0.19	>0.050	0.80	0.006
	Bulb	-0.48	>0.050	-0.34	>0.050
A. corolinianum	Flowers	0.22	>0.050	0.40	>0.050
	Leaves	-0.47	>0.050	0.02	>0.050
	Bulb	0.18	>0.050	0.65	0.042
A. elatum	Flowers	-0.42	>0.050	0.77	0.009
	Leaves	-0.11	>0.050	-0.23	>0.050
	Bulb	-0.33	>0.050	0.13	>0.050
A. hymenorhizum	Flowers	0.05	>0.050	0.32	>0.050
	Leaves	-0.58	>0.050	0.04	>0.050
	Bulb	-0.38	>0.050	-0.64	0.047
A. longicuspis	Flowers	0.34	>0.050	-0.00	>0.050
	Leaves	0.05	>0.050	0.18	>0.050
	Bulb	0.10	>0.050	0.44	>0.050
A. nutans	Flowers	-0.51	>0.050	0.30	>0.050
	Leaves	-0.20	>0.050	-0.50	>0.050
	Bulb	-0.31	>0.050	-0.20	>0.050

A. obliquum	Flowers	-0.16	>0.050	-0.40	>0.050
	Leaves	0.24	>0.050	-0.50	>0.050
	Bulb	0.16	>0.050	0.06	>0.050
A. oschanii	Flowers	0.23	>0.050	-0.10	>0.050
	Leaves	-0.08	>0.050	0.03	>0.050
	Bulb	0.14	>0.050	0.19	>0.050
A. pamiricum	Flowers	-0.30	>0.050	-0.36	>0.050
	Leaves	0.12	>0.050	0.10	>0.050
	Bulb	0.20	>0.050	0.61	>0.050
A. ramosum	Flowers	-0.01	>0.050	-0.04	>0.050
	Leaves	-0.24	>0.050	-0.06	>0.050
	Bulb	0.37	>0.050	-0.33	>0.050
A. sativum	Flowers	0.09	>0.050	0.66	0.038
	Leaves	0.19	>0.050	-0.59	>0.050
	Bulb	0.21	>0.050	0.12	>0.050
A. schoenoprasum	Flowers	-0.08	>0.050	-0.23	>0.050
	Leaves	0.21	>0.050	-0.21	>0.050
	Bulb	0.21	>0.050	0.31	>0.050
A. schugnanicum	Flowers	0.49	>0.050	0.68	0.031
	Leaves	-0.26	>0.050	-0.04	>0.050
	Bulb	-0.48	>0.050	0.55	>0.050
A. senescens	Flowers	0.06	>0.050	-0.33	>0.050
	Leaves	-0.05	>0.050	0.06	>0.050
	Bulb	-0.15	>0.050	0.23	>0.050
A. suworowii	Flowers	-0.53	>0.050	0.15	>0.050
	Leaves	-0.49	>0.050	0.14	>0.050
	Bulb	0.15	>0.050	-0.28	>0.050

It's essential to highlight the correlation indices observed in two endemic Tajik species, *A. shugnanicum* and *A. pamiricum*. A moderate positive correlation was noted in the flower extracts of *A. shugnanicum* ($r = 0.68$, $p < 0.031$), suggesting a link between antioxidant activity and anti-staphylococcal effect. However, the extracts of *A. pamiricum* did not exhibit a significant correlation with their antibacterial impact on *S. aureus* across the studied plant parts. Furthermore, flower extracts of *A. sativum* and bulb extracts of *A. carolinianum* also demonstrated moderate positive correlations ($r = 0.66$, $p = 0.038$ and $r = 0.65$, $p = 0.042$, respectively), indicating a noteworthy relationship between antioxidant activity and antibacterial efficacy. In contrast, bulb extracts of *A. hymenorhizum* presented a significant moderate negative correlation ($r = -0.64$, $p = 0.047$) between antioxidant activity and anti-staphylococcal effect, providing interesting insight into the complex interactions between these bioactive compounds.

For the remaining *Allium* species – including *A. longicuspis*, *A. nutans*, *A. obliquum*, *A. oschaninii*, *A. ramosum*, *A. sativum*, *A. schoenoprasum*, *A. senescens*, and *A. suworowii* – extracts

from both aerial and subterranean parts exhibited no significant correlation between the analyzed parameters ($p > 0.05$).

Remarkably, we found no significant correlation between TPC and anti-staphylococcal activity in any of the plant extracts studied, encompassing both above ground and underground parts.

III.3.2. Antibacterial effects of plant extracts against Pseudomonas aeruginosa. Although individual plant parts occasionally exhibit significant correlations, our study generally found a lack of consistent, statistically significant relationships between TPC or antioxidant activity and antibacterial activity against *P. aeruginosa*, as detailed in Table 3.

Table 3. Correlation of plant extracts' total polyphenol content and antioxidant activity with antibacterial activities against *Ps. aeruginosa*.

Species	Plantpart	Total Polyphenol		AntioxidantActivity	
		r	P	r	p
A. altaicum	Flowers	0.44	>0.050	-0.37	>0.050
	Leaves	0.34	>0.050	0.13	>0.050
	Bulb	0.08	>0.050	0.38	>0.050
A. corolinianum	Flowers	0.18	>0.050	0.29	>0.050
	Leaves	-0.55	>0.050	0.37	>0.050
	Bulb	-0.61	>0.050	0.25	>0.050
A. elatum	Flowers	0.02	>0.050	-0.27	>0.050
	Leaves	0.03	>0.050	-0.29	>0.050
	Bulb	-0.35	>0.050	-0.02	>0.050
A. hymenorhizum	Flowers	*		*	
	Leaves	0.07	>0.050	-0.07	>0.050
	Bulb	0.12	>0.050	-0.59	>0.050
A. oschanii	Flowers	0.18	>0.050	0.10	>0.050
	Leaves	-0.04	>0.050	-0.50	>0.050
	Bulb	0.36	>0.050	-0.67	0.049
A. pamiricum	Flowers	0.13	>0.050	-0.22	>0.050
	Leaves	0.12	>0.050	-0.46	>0.050
	Bulb	-0.04	>0.050	0.39	>0.050
A. sativum	Flowers	-0.36	>0.050	0.40	>0.050
	Leaves	0.24	>0.050	-0.01	>0.050
	Bulb	-0.46	>0.050	-0.69	0.026
A. schoenoprasum	Flowers	0.26	>0.050	0.20	>0.050
	Leaves	-0.87	0.001	0.23	>0.050
	Bulb	-0.64	0.046	-0.68	0.03
A. schugnanicum	Flowers	0.17	>0.050	-0.45	>0.050
	Leaves	-0.54	>0.050	-0.32	>0.050
	Bulb	-0.17	>0.050	0.27	>0.050
A. senescens	Flowers	0.49	>0.050	-0.14	>0.050
	Leaves	0.16	>0.050	-0.47	>0.050
	Bulb	-0.02	>0.050	0.21	>0.050
A. suworowii	Flowers	0.15	>0.050	0.07	>0.050
	Leaves	0.17	>0.050	0.15	>0.050
	Bulb	-0.11	>0.050	0.69	0.027

* indicates that it was impossible to ascertain the correlation, as the antifungal properties were uniform across all samples.

A notable exception was the moderate positive correlation observed in the antioxidant activity of *A. suworowii* bulb extracts, which corresponded with an inhibitory effect on the growth of *P. aeruginosa* (r = 0.69, p = 0.027). In contrast, bulb extracts from *A. oschanii*, *A. schoenoprasum*, and *A. sativum* displayed moderate negative correlations with antibacterial activity (r = -0.67, p = 0.049; r = -0.68, p = 0.030; and r = -0.69, p = 0.026, respectively). This suggests an inverse relationship where higher antioxidant activity in these extracts is linked to decreased antibacterial efficacy against *Ps. aeruginosa*. Furthermore, our study uncovered a high negative correlation between the TPC in *A. schoenoprasum* leaves and their antibacterial efficacy against Ps. aeruginosa (r = -0.87, p = 0.001), marking this as the most significant correlation observed in our research. A similar trend was noted in the bulb extracts of the same species (r = -0.64, p = 0.046).

III.3.4. Antibacterial effects of plant extracts against K.pneumoniae.

Table 4 elucidates the relationship between TPC and antioxidant activity in various parts of *Allium* species, alongside their antibacterial activity against *K. pneumoniae*. The correlation coefficients (r) span a range from moderately negative (e.g., -0.61 in the bulb of *A. altaicum* for TPC)

Table 4. Correlation of total polyphenol content and antioxidant activity with antibacterial activity against *Klebsiella pneumoniae*

Species	Plant part	Total Polyphenol		Antioxid antactivity	
		r	P	r	p
A. altaicum	Flowers	-0.39	>0.05	0.51	>0.05
	Leaves	-0.01	>0.05	-0.55	>0.05
	Bulb	-0.61	>0.05	0.21	>0.05
A. carolinianum	Flowers	-0.18	>0.05	-0.06	>0.05
	Leaves	0.11	>0.05	-0.49	>0.05
	Bulb	-0.07	>0.05	0.51	>0.05
A. elatum	Flowers	0.18	>0.05	-0.35	>0.05
	Leaves	0.55	>0.05	-0.32	>0.05
	Bulb	-0.51	>0.05	0.44	>0.05
A. hymenorhizum	Flowers	0.17	>0.05	0.50	>0.05
	Leaves	*		*	
	Bulb	-0.49	>0.05	0.08	>0.05
A. oschaninii	Flowers	-0.28	>0.05	-0.11	>0.05
	Leaves	-0.27	>0.05	-0.28	>0.05
	Bulb	0.54	>0.05	-0.03	>0.05
A. pamiricum	Flowers	-0.59	>0.05	0.04	>0.05
	Leaves	-0.24	>0.05	-0.28	>0.05
	Bulb	-0.19	>0.05	0.04	>0.05
A. ramosum	Flowers	-0.11	>0.05	-0.39	>0.05
	Leaves	-0.24	>0.05	0.07	>0.05
	Bulb	0.08	>0.05	-0.6	>0.05
A. sativum	Flowers	0.43	>0.05	0.04	>0.05

	Leaves	-0.29	>0.05	0.40	>0.05
	Bulb	-0.06	>0.05	-0.22	>0.05
A. senescens	Flowers	-0.45	>0.05	0.08	>0.05
	Leaves	-0.39	>0.05	0.01	>0.05
	Bulb	0.44	>0.05	0.15	>0.05
A. suworowii	Flowers	0.23	>0.05	-0.27	>0.05
	Leaves	0.21	>0.05	0.21	>0.05
	Bulb	-0.05	>0.05	0.26	>0.05

* indicates that it was impossible to ascertain the correlation, as the antifungal properties were uniform across all samples

to moderately positive (e.g., 0.55 in the leaves of *A. elatum* for TPC). However, these correlations do not achieve statistical significance, as indicated by p-values exceeding 0.05. Noteworthy observations include *A. altaicum*'s bulb demonstrating a negative trend between TPC and antibacterial activity, a pattern also observed in *A. carolinianum* and *A. pamiricum*, albeit these trends did not reach statistical significance. In contrast, the bulb of *A. oschaninii* revealed a moderately positive correlation for TPC, diverging from the weaker correlations seen in its flowers and leaves. For *A. sativum*, flower extracts showed a low, non significant positive correlation for TPC, while the leaves indicated a positive correlation for antioxidant activity. The overall lack of statistically significant correlations suggests that there may not be a consistent or direct relationship between the TPC or antioxidant activity of these plant extracts and their antibacterial efficacy against *K. pneumoniae* across the *Allium* species and plant parts studied.

III.3.5. Antibacterial effects of plant extracts against Escherichia coli.

Table 5 details the correlation analysis between TPC or antioxidant activity and antibacterial efficacy

Table 5. Correlation between polyphenol content and antioxidant activity with antibacterial properties against E. coli.* indicates that it was impossible to ascertain the correlation, as the antifungal properties were uniform across all samples

Species	Plant part	Total Polyphenol		Antioxidant Capacity	
		r	P	r	p
A. altaicum	Flowers	0.5	>0.05	0.24	>0.05
	Leaves	0.25	>0.05	-0.12	>0.05
	Bulb	-0.15	>0.05	-0.60	>0.05
A. hymenorhizum	Flowers	-0.94	0,000	0.50	>0.05
	Leaves	0.34	>0.05	-0.03	>0.05
	Bulb	0.16	>0.05	0.57	>0.05
A. oschaninii	Flowers	0.20	>0.05	0.13	>0.05
	Leaves	-0.40	>0.05	-0.03	>0.05
	Bulb	0.1	>0.05	-0.43	>0.05
A. ramosum	Flowers	0.22	>0.05	0.21	>0.05
	Leaves	-0.19	>0.05	0.02	>0.05
	Bulb	0.51	>0.05	0.09	>0.05
A. sativum	Flowers	-0.37	>0.05	0.11	>0.05
	Leaves	*		*	
	Bulb	0.36	>0.05	0.20	>0.05

against *E. coli* in various plant parts of selected *Allium* species. The majority of our findings, particularly for *A. altaicum*, *A. oschaninii*, *A. ramosum*, and *A. sativum*, indicate non-significant correlations. This suggests an uncertain relationship between these factors and the antibacterial properties against *E. coli*. Notably, however, an exception is observed in the flowers of *A. hymenorhizum*. Here, a strongly negative correlation is seen, indicating a potential decline in antibacterial effectiveness against *E. coli* with increased polyphenol levels. In our correlation analysis, the data for *A. altaicum*, *A. oschaninii*, *A. ramosum*, and *A. sativum* predominantly show non-significant results ($p > 0.05$). These outcomes do not substantiate a clear relationship between TPC or antioxidant activity and antibacterial efficacy against *E. coli*. In contrast, the flowers of *A. hymenorhizum* display a pronounced negative correlation ($r = -0.94$) with a statistically significant p-value ($p < 0.01$). This marked correlation implies a tendency for reduced antibacterial properties against *E. coli* as the TPC increases. This inverse relationship is of particular interest and merits further investigation to understand the underlying mechanisms driving this interaction.

Antifungal effects of plant extracts against *C. albicans*. Table 6 presents the correlations between the TPC and antioxidant activity in various parts of *Allium* species and their antifungal properties. Overall, the data predominantly indicate no significant correlations between the levels of polyphenol or antioxidant activity and the antifungal efficacy ($p > 0.05$). However, there are notable

Table 6. Correlation between polyphenol content and antioxidant activity with antifungal properties. * indicates that it was impossible to ascertain the correlation, as the antifungal properties were uniform across all samples.

Species	Plantpart	Total Polyphenol		AntioxidantActivity	
		r	P	r	p
A. altaicum	Flowers	*	>0.050	*	>0.050
	Leaves	-0.41	>0.050	-0.48	>0.050
	Bulb	-0.39	>0.050	-0.37	>0.050
A. carolinianum	Flowers	-0.38	>0.050	0.23	>0.050
	Leaves	-0.14	>0.050	-0.38	>0.050
	Bulb	0.32	>0.050	0.19	>0.050
A. elatum	Flowers	-0.28	>0.050	0.37	>0.050
	Leaves	-0.22	>0.050	0.17	>0.050
	Bulb	-0.47	>0.050	0.15	>0.050
A. hymenorhizum	Flowers	-0.17	>0.050	0.23	>0.050
	Leaves	0.61	>0.050	0.58	>0.050
	Bulb	0.26	>0.050	-0.32	>0.050
A. longicuspis	Flowers	0.13	>0.050	-0.11	>0.050
	Leaves	0.18	>0.050	-0.17	>0.050
	Bulb	0.07	>0.050	-0.17	>0.050
A. nutans	Flowers	-0.13	>0.050	-0.51	>0.050
	Leaves	*		*	
	Bulb	-0.09	>0.050	0.05	>0.050
A. obliquum	Flowers	-0.13	>0.050	-0.18	>0.050
	Leaves	-0.12	>0.050	-0.12	>0.050

	Bulb	0.29	>0.050	0.19	>0.050
A. oschaninii	Flowers	0.03	>0.050	0.07	>0.050
	Leaves	-0.35	>0.050	-0.73	0.017
	Bulb	-0.45	>0.050	0.01	>0.050
A. pamiricum	Flowers	0.2	>0.050	0.07	>0.050
	Leaves	-0.11	>0.050	0.08	>0.050
	Bulb	0.09	>0.050	0.22	>0.050
A. ramosum	Flowers	0.18	>0.050	0.52	>0.050
	Leaves	0.67	0.033	-0.34	>0.050
	Bulb	0.38	>0.050	0.02	>0.050
A. sativum	Flowers	0.08	>0.050	-0.27	>0.050
	Leaves	0.31	>0.050	-0.46	>0.050
	Bulb	-0.17	>0.050	-0.26	>0.050
A. schoenoprasum	Flowers	-0.32	>0.050	-0.24	>0.050
	Leaves	-0.25	>0.050	0.44	>0.050
	Bulb	0.34	>0.050	-0.11	>0.050
A. schugnanicum	Flowers	-0.41	>0.050	-0.19	>0.050
	Leaves	-0.38	>0.050	0.79	0.007
	Bulb	-0.23	>0.050	-0.19	>0.050
A. senescens	Flowers	-0.4	>0.050	0.08	>0.050
	Leaves	0.07	>0.050	-0.14	>0.050
	Bulb	-0.16	>0.050	0.01	>0.050
A. suworowii	Flowers	0.61	>0.050	0.18	>0.050
	Leaves	-0.45	>0.050	0.28	>0.050
	Bulb	-0.03	>0.050	0.51	>0.050

exceptions. For instance, leaves of *A. oschaninii* display a high negative correlation with antioxidant activity in relation to antifungal properties ($r = -0.73$, $p = 0.017$). This suggests that increased antioxidant activity is linked to reduced antifungal effectiveness. In contrast, leaves of *A. ramosum* exhibit a moderately positive and significant correlation with TPC ($r = 0.67$, $p = 0.033$), indicating a potential association between higher TPC and enhanced antifungal activity. Additionally, a high positive correlation with antioxidant activity is observed in *A. schugnanicum* leaves ($r = 0.79$, $p = 0.007$).Conversely, in the case of *A. altaicum* flowers and *A. nutans* leaves, our analysis could not establish any correlation. This was due to the uniformity of antifungal properties across the samples, which precludes the computation of a correlation coefficient. Correlation analysis requires variability in both variables being compared.

III.3.6. Altitudinal influence on polyphenol, antioxidant, and antimicrobial activities in A. oschaninii and A. suworowii.

TPC, antioxidant activity, as well as antibacterial and antifungal activities of *A. oschaninii* samples were evaluated across various locations spanning altitudes from 1,240 meters to 2,320 meters above sea level (Table 7). No discernible trend was observed in these variables within the selected

Table 7. Polyphenol content, antioxidant activity, antibacterial; and antifungal activity of *A. oschanini* samples from a variety of location with an altitude ranging from 1240 meters to 2320 meters above sea level.

Location	Elevation (above the sea level, m)	Plant part	Total Polyphenol μg GAEg^{-1}	Antioxidant activity μg TE g^{-1}	Biological activity			
					Antibacterial			Antifungal
					S. aureus	*Ps. aeruginosa*	*E. coli*	*C. albicans*
Botanical Garden. MBAR(Mountainous-Badakhshan Autonomous Region)	2320	Flowers Leaves Bulb	11.66±0.04 20.84±0.05 22.22±0.09	11.12±0.02 11±0.03 11.16±0.04	7.90±0.18 7.20±0.13 8.60±0.22	10.70±0.33 7.70±0.15 10.80±0.20	8.00±0.15 7.90±0.18 8.90±0.28	10.80±0.39 10.40±0.34 10.40±0.34
Khushyori. VarzobGorge	1449	Flowers Leaves Bulb	11.74±0.01 19.4±0.09 22.22±0.05	10.5±0.01 9.24±0.05 11.3±0.02	10.50±0.31 8.10±0.18 11.00±0.21	10.90±0.35 8.10±0.18 10.90±0.23	8.20±0.13 7.20±0.13 8.30±0.15	10.40±0.34 10.40±0.34 10.40±0.34
Vorukh. Isfara	1400	Flowers Leaves Bulb	13.36±0.07 19.14±0.06 22.06±0.13	10.26±0.13 9.3±0.05 11.38±0.02	16.50±0.43 11.10±0.28 19.50±0.31	10.10±0.18 7.60±0.27 10.30±0.30	7.40±0.16 7.20±0.13 8.10±0.18	10.40±0.34 10.40±0.34 10.40±0.34
Yafrak. Ramit Gorge.	1260	Flowers Leaves Bulb	10.92±0.04 20.08±0.03 20.64±0.03	8.84±0.02 9.76±0.03 10.74±0.02	10.90±0.28 9.50±0.22 18.00±0.37	10.60±0.22 9.90±0.28 10.90±0.28	10.20±0.20 9.70±0.21 13.80±0.20	19.60±0.34 10.80±0.39 25.00±0.37
Kondara. Varzob Gorge	1240	Flowers Leaves Bulb	11.82±0.02 19.14±0.11 22.64±0.11	10.3±0.02 9.6±0.06 11.3±0.03	11.20±0.29 10.30±0.40 15.10±0.28	7.80±0.29 7.60±0.16 10.10±0.18	7.40±0.16 7.20±0.13 8.60±0.13	10.80±0.39 10.40±0.34 10.40±0.34

range of altitudes. Similarly, the TPC, antioxidant, antibacterial, and antifungal activities of *A. suworowii* samples were assessed at altitudes ranging from 1,187 meters to 1,798 meters above sea level. Again, no visible trend was evident in the variables across the studied altitudinal gradient. It was noted that the TPC is generally higher in bulbs and leaves than in flowers. Antioxidant activity appeared relatively consistent across all plant parts and locations (Table 8). The antibacterial activity of *A. suworowii* was comparable to that of *A. oschaninii* samples. Notably, the antifungal activity against *C. albicans* was significant in bulb and flower samples from the Varzob River region, exhibiting values exceeding 19, in contrast to other samples. TPC is typically higher in bulbs and leaves than in flowers (Figure 1A), with the highest values observed in bulbs from the MBAR and Kondara locations, exceeding 22 μg GAE g^{-1}. antioxidant activity was found to be relatively uniform across all plant parts and locations. Figure 1B illustrates that, generally, bulbs exhibit higher TPC, antioxidant activity, and biological activity compared to flowers and leaves.

Table 8. Quantitative content of total polyphenol, total antioxidant content, and antimicrobial activity of the aboveground and underground organs of *A. suworowii* Regel depending on the altitude of growth.

	Elevation (above the sea level, m)	**Plant part**	**Antioxidant activity** μg TE g^{-1} **Total**	**Polyphenol** μg GAE g^{-1}	**Biological activity**			
					Antibacterial			***Antifungal***
					S. aureus	***Ps. aerug***	***E. coli***	***C. albicans***
Dara, RamitGorge.	1798	Flowers	12.72±0.13	10.48±0.02	8.00±0.21	7.90±0.23	7.30±0.15	9.90±0.28
		Leaves	20.22±0.02	9.38±0.06	7.20±0.13	7.30±0.15	7.30±0.15	7.70±0.15
		Bulb	21.98±0.07	11.48±0.03	10.40±0.27	8.60±0.22	8.00±0.15	11.00±0.26
Siyokuh. Gissar Valley.	1492	Flowers	12.02±0.13	10.68±0.04	7.90±0.18	7.30±0.15	7.20±0.13	9.90±0.23
		Leaves	20.22±0.02	9.6±0.04	7.30±0.15	7.40±0.16	7.20±0.13	7.90±0.23
		Bulb	20.88±0.05	11.58±0.02	10.30±0.26	8.30±0.26	8.00±0.15	10.20±0.20
Varzob River Basin. Varzob Gorge.	1436	Flowers	11.66±0.05	10.48±0.01	10.30±0.21	8.40±0.16	10.40±0.27	19.00±0.37
		Leaves	20.7±0.07	9.36±0.05	9.30±0.21	7.40±0.16	7.90±0.18	10.10±0.35
		Bulb	21.16±0.03	11.24±0.02	11.60±0.27	9.80±0.20	11.20±0.29	19.30±0.40
Yafrak. Ramit Gorge.	1370	Flowers	11.78±0.13	10.78±0.03	15.50±0.31	7.40±0.16	7.60±0.22	7.80±0.20
		Leaves	21.54±0.04	10.82±0.11	10.20±0.39	7.40±0.16	7.30±0.15	7.30±0.15
		Bulb	21.14±0.04	11.16±0.03	12.30±0.54	8.60±0.22	8.60±0.16	10.80±0.25
Kondara. Varzob Gorge	1187	Flowers	12.68±0.15	9.92±0.07	9.90±0.32	7.30±0.15	7.90±0.23	8.30±0.26
		Leaves	20.02±0.05	9.02±0.04	8.00±0.21	7.20±0.13	7.30±0.15	7.60±0.22
		Bulb	21.60±0.03	10.4±0.02	11.00±0.26	8.30±0.15	8.40±0.16	11.20±0.29

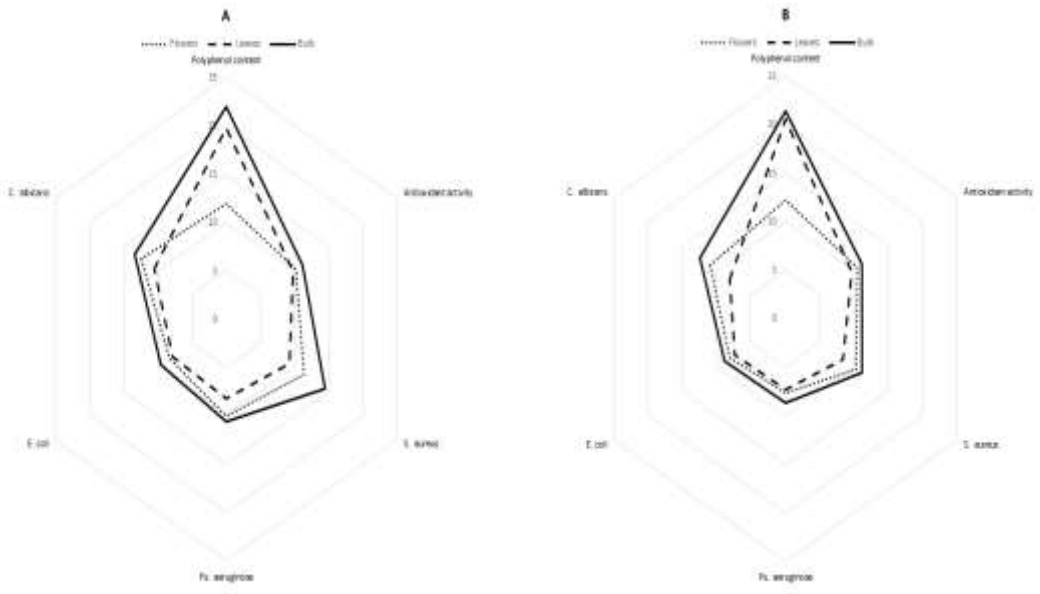

Figure 1. Quantitative content of total polyphenol, antioxidant activity, and antimicrobial activity of the aboveground and underground organs of *A. oschaninii* (A) and *A. suworowii* (B).

DISCUSSION

The genus *Allium* encompasses a diverse array of wild species, a significant number of which have been extensively utilized within the realms of traditional and folklore medicine. Conversely, certain species within this genus remain relatively underexplored or possess predominantly regional relevance. These species harbor the potential to act as repositories of natural bioactive compounds, thus proffering substantial health benefits [39].Species such as *A. cepa*, *A. sativum* [40, 41]. *A. fistulosum*, *A. schoenoprasum* [42], *A. ursinum*, *A. flavum*, *A. scorodoprasum*, *A. vineale*and *A. atroviolaceum* are instrumental in sustaining human health [43, 44]. *Allium* species offer a range of health benefits, including antimicrobial, antifungal, antiviral, antioxidant, anticancer, antihypertensive, antihyperlipidemic, antiatherosclerotic, antidiabetic, and antirheumatic properties. Plants in the genus *Allium* also exhibit cardiovascular protection and may affect male fertility [45]. Beyond their immediate medicinal applications, the wild *Allium* species population embodies a crucial source of genetic and metabolomic variability. This variability is not merely of academic interest but holds practical implications for the genetic modification and enhancement of cultivated *Allium* species, offering pathways to augment their health-promoting properties and agricultural viability.

A substantial body of scholarly research delineates the chemical composition, biological activity, and consequent health benefits associated with the most prevalent cultivated *Allium* species, notably garlic (*A. sativum*) [46, 47] and Chives (*A. schoenoprasum*) [48]. In contrast, much less is known about the chemical composition and potential health benefits of other wild *Allium* species. There have been only a few attempts to establish correlations between the chemical composition and biological properties of extracts from various *Allium* species, particularly the Tajik endemics *A. pamiricum* and *A. schugnanicum*.

We conducted a comprehensive analysis to elucidate the relationships between the polyphenolic content, antioxidant activity, and antimicrobial properties across various parts of fifteen *Allium* species. This analysis encompassed species endemic to Tajikistan, such as *A. pamiricum* and *A. schugnanicum,* in addition to species with a more limited distribution area, including *A. suworowii*, *A. oschaninii, A. elatum,* and *A. altaicum*. Notably, data concerning the phytochemistry and biological activity of extracts from these species are very limited [49]. Considering the escalating interest in the medicinal properties of plant-based compounds, especially for their potential role in ameliorating aging-associated diseases, the genus *Allium* emerges as a particularly promising candidate due to its diverse bioactive potentials [50].

Bulbs of the *Allium* genus are generally recognized for their high TPC. For instance, *Allium nigrum L.* and *Allium subhirsutum* L. have been reported to exhibit the highest levels of total phenols in their bulbs [51]. Our investigation into the TPC across various *Allium* species reveals a complex landscape of variability among different plant parts, with flowers demonstrating notably lower variability compared to leaves and bulbs. Specifically, the TPC in flowers exhibited a narrow range, from 10.50 μg GAE g^{-1} in *A. ramosum* to 16.50 μg GAE g^{-1} in *A. obliquum*, indicating less pronounced variability in this component of the plant. In contrast, leaves presented a wider spectrum of TPC, ranging from10.84 μg GAE g^{-1} to 21.06 μg GAE g^{-1}, with significant interspecies differences.

Prior research on *Allium ursinum* L. identified the highest levels of TPC in the flowers relative to the leaves [52]. Notably, *A. suworowii* and *A. oshaninii* were distinguished by their high polyphenol levels, suggesting that specific species may serve as more potent sources of these compounds. Bulb extracts demonstrated even greater variability, with TPC exceeding 20 μg GAE g^1 in several species, among which *A. oshaninii*, presented the highest level at 23.28 μg GAE g^{-1}. This supports the notion that bulbs are typically the richest source of polyphenols within the *Allium* genus, albeit with significant interspecies variation. The Tajik endemic species *A. pamiricum* and *A. schugnanicum* exhibited low and consistent TPC. The described variability highlights the necessity for further investigation into the specific metabolic pathways and bioactive compound distributions within each species [53].

The investigation into the antioxidant activity across different plant parts of the *Allium* genus revealed variations within a relatively narrow spectrum. Notably, there was an absence of a uniform pattern in the distribution of antioxidant activities among the studied *Allium* species. Specifically, *A. carolinianum* and *A. elatum* exhibited heightened antioxidant activities in their floral segments compared to other plant parts. This suggests a particular enrichment of bioactive constituents in the flowers of these species, which may contribute to their elevated antioxidant capacities.

While previous studies reported a direct correlation between TPC and antioxidant activity [54, 55], we did not observe this trend in our research. This discrepancy underscores the potential for additional, unmeasured factors to influence antioxidant activity, suggesting that the relationship between polyphenols and antioxidant efficacy may be more complex than previously understood. Accordingly, our findings highlight the importance of broadening the scope of future studies to include a wider range of bioactive compounds and consider the interplay of various factors that may impact antioxidant activity.

Our investigation revealed distinct correlations between antioxidant activity and antibacterial efficacy across different parts of selected *Allium* species. Notably, antioxidant activities in *A. altaicum* leaves and *A. elatum* flowers exhibited positive correlations with antibacterial effects against *Staphylococcus aureus*. Additionally, the bulbs of *A. suworowii* demonstrated a moderate positive correlation in this regard. Conversely, negative correlations were identified for *P. aeruginosa* in the bulbs of *A. oschaninii*, *A. schoenoprasum*, and *A. sativum*. Particularly striking was the strong negative correlation between antioxidant activity and the anti-E. coli effect observed in *A. hymenorhizum* flowers. Furthermore, the leaves of *A. oschaninii* and *A. schugnanicum* exhibited contrasting correlations with antibacterial effects, underscoring the complex interplay between antioxidant activity and antibacterial efficacy within these species. These findings suggest that the relationship between antioxidant activity and antibacterial effects is not uniform across all *Allium* species or bacterial strains. The observed variability implies that factors beyond antioxidant activity per se may influence the antibacterial potential of these plant extracts.

The observed lack of a direct and robust correlation between the TPC and the antibacterial and antifungal activities of *Allium* extracts in our investigation suggests that alternative phytochemicals might be responsible for the observed biological activity. The relationship between the TPC and the antioxidant capacity with antibacterial and antifungal activities presented a

multifaceted and diverse landscape. Noteworthy is the presence of both high positive and moderate negative correlations with anti-S. aureus effects. Additionally, moderate correlations were observed with anti - *P. aeruginosa*, and there were no significant correlations with *K. pneumoniae*. Intriguingly, *A. hymenorhizum* flowers exhibited a pronounced negative correlation with anti-E. coli activity. These findings imply that the antibacterial effectiveness of *Allium* extracts cannot be exclusively determined by their TPC or antioxidant property. The *Allium* genus is recognized for its richness in sulfur-containing compounds such as allicin, acclaimed for their antioxidant and anti-inflammatory properties. Allicin, an organic sulfur compound, serves as a broad-spectrum antibacterial agent endowed with a plethora of biological functions. These functions encompass reducing inflammation and contributing to the lowering of blood pressure and lipid levels [56]. Classified within the organ sulfur compounds, allicin is derived from garlic. Specifically, it is produced through the mechanical action of crushing or chopping garlic bulbs, which catalyzes the release of this potent compound. Notable for its strong odor, allicin is celebrated for its potential health benefits and antimicrobial properties. It plays a pivotal role in imparting the distinctive smell and flavor characteristic of garlic. Current scientific evidence supports the notion that allicin could serve as a therapeutic alternative for the treatment of cardiovascular diseases and their associated risk factors [57, 58].

Environmental factors significantly influence the biosynthesis of secondary metabolites and biological activity in *Allium* genus plants [59]. Environmental conditions under which these plants are grown have a notable impact on the total phenolic content and the in vitro antioxidant potential in the bulbs and leaves of onion varieties. Additionally, the content of TPC and the antioxidant activity value in the leaves of wild garlic increase with plant maturity. Interestingly, *A. oschaninii* and *A. suworowii* [60] demonstrated consistent levels of antioxidant activity across all plant parts and locations. This finding suggests the potential for these species as reliable sources of bioactive compounds with stable therapeutic properties. The study did not detect a visible trend in TPC, antioxidant, antibacterial, or antifungal activities with changes in altitude. In our case, the absence of a visible trend between altitude and biological activities suggests that environmental factors beyond altitude might play a more significant role in shaping these properties. Future studies incorporating diverse geographical locations could shed light on the influence of other environmental factors.

CONCLUSION

Amidst the escalating interest in natural bioactive compounds for their health benefits, our comprehensive investigation delves into the polyphenolic content, antioxidant capacity, and antimicrobial properties of fifteen *Allium* species, which include several lesser-known wild varieties. The outcomes of this investigation delineate a pronounced heterogeneity in the bioactive potential amongst the examined species and their constituent parts, thereby emphasizing their distinct species-specific and part-specific phytochemical compositions. Remarkably, our analysis identified that bulbs often exhibit the highest concentration of polyphenols, positioning them as valuable sources for phytochemical extraction.

This research contributes significantly to the existing corpus of knowledge by elucidating the vast array of bioactive compounds inherent to the *Allium* genus, thus bolstering the argument for a

sophisticated, dual-focused approach that prioritizes both species and anatomical sections in the exploitation of *Allium*'s therapeutic capabilities. The manifold properties unearthed through this study herald a promising pathway for the formulation of naturalistic therapeutics and pharmaceutical interventions.

Looking ahead, it is imperative that subsequent scholarly endeavors strive to dissect the intricate biochemical mechanisms that underpin the therapeutic efficacy of these phytochemicals. Such endeavors should aim to meticulously explore the unique attributes inherent to each species and anatomical segment. By tailoring future investigations to align with specific therapeutic objectives especially by concentrating on species and plant parts that have demonstrated efficacy against particular pathogens the scientific community may expedite the advent of precise and potent treatment modalities.

This nuanced scholarly discourse not only underscores the critical need for targeted research within the domain of natural bioactive compounds but also sets the stage for transformative advancements in the development of phytochemically based therapeutic solutions.

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ETHICS DECLARATIONS

Ethics approval and consent to participate

Not applicable.

CONFLICTS OF INTEREST

The authors declare no conflict of interest